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Magnetically Tunable Ferrite-Dielectric Left-Handed Metamaterial

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Abstract—In this paper, a magnetically tunable metamaterial is proposed and studied. The metamaterial is based on the combination of ferrite sheets and dielectric rods. The tunable property is originated from the ferromagnetic resonance and electric response of dielectric rods. The retrieved electromagnetic parameters and transmission characteristic showed that by simultaneously inspiring the ferromagnetic resonance and electric resonance, composite metamaterial can possess double-negative band in the resonant state. Moreover, this band was tunable by adjusting applied magnetic fields. The simulations and experiments verified that the composite metamaterial clearly displayed a tunable feature. The proposed method is simple in designing tunable metamaterials.

1. INTRODUCTION

Metamaterials, especially double-negative left-handed metamaterial, have attracted much attention. Based on the pioneer works on metallic array [1] and split ring resonator (SRR) array [2], the first artificial left-handed metamaterial was experimentally proved by combining these two arrays [3]. Most left-handed metamaterials are constructed using metallic patterns such as Ω-shaped structures, S-shaped structures and fishnet structures [4–6]. Usually, metallic patterns have conductive losses and anisotropic electromagnetic responses. Conductive loss increases with frequency notably up to infrared and optical frequencies, where the remarkably large losses will eliminate electromagnetic properties.

Dielectric inclusions provide a novel mechanism for the creation of magnetic or electric resonance via displacement currents. This mechanism offers a simpler and more versatile route for the fabrication of isotropic metamaterials operating at higher frequencies. Microwave ceramics with high permittivity and low loss were made into rods, spheres and cubic resonators [7, 8]. The electromagnetic wave interaction of dielectric particles can exhibit a strong magnetic or electric resonance, and negative permeability or permittivity can be produced. However, these composites have fixed operating frequencies once they are fabricated, and their working band is narrow far away from application requirements. To overcome these obstacles, it is desirable to design structures with tunable properties. Some possible implementations for the tunable metamaterials have been proposed. For example, the composite of ferromagnetic materials could be a magnetically tunable metamaterial. He et al. used yttrium iron garnet (YIG) sheets and copper wires to make tunable refractive index metamaterial [9]. Kang et al. applied YIG rods with SRRs/wires to display a tunable double-negative metamaterial [10]. The electrically tunable metamaterials can use ferroelectric to offer tunable dielectric permittivity by bias electric field [11]. However, the electrically tunable material needs very strong electric fields and has a narrow tunable range. Meanwhile, the thermally tunable materials are also studied, which depend on the changes in the dielectric constant of ceramics by temperature [12]. For a thermally tunable material, it is difficult to control the temperature accurately, and its response is slow since it needs time to get a

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uniform temperature distribution. The magnetically tunable material has obvious advantages. It offers relatively wide tunable range and has a rapid response in the applied magnetic fields.

In this paper, we report a magnetically tunable metamaterial based on the combination of ferrite sheets and dielectric rods. The electromagnetic properties of the metamaterials were investigated by simulations and experiments. Our results demonstrate that effective permittivity and permeability of the metamaterial can be tuned by applied magnetic field. Ferrite-dielectric metamaterial can effectively avoid coupling effect compared with ferrite-metal wires structures [13] or dielectric metamaterials [14].

2. DESIGN AND SIMULATION

Figure 1 shows the schematic diagram of the magnetically tunable metamaterial. The metamaterial is composed of three dielectric rods and three ferrite sheets. The full wave finite element method simulator (Ansoft HFSS) was used to perform the numerical simulation. The proposed model was placed in an x-band waveguide, which has a cross-section of $22.86 \times 10.16\,\mathrm{mm}^2$ and works in 8–12 GHz. The ferromagnetic material is YIG ferrite, whose saturation magnetization is 1780 Gs and resonant bandwidth 30 Oe. The relative permittivity can be recognized as a constant about 14.4 at microwave frequencies. The permittivity of dielectric rod is 100, and the loss tangent is 0.0016. The ferrite sheets are $22.86 \times 3 \times 0.4\,\mathrm{mm}^3$, and the rods are $1.5 \times 1.5 \times 10.16\,\mathrm{mm}^3$ in size, respectively. An electromagnetic wave was incident along the Y-axis. The boundary condition for the side walls of the waveguide was set as perfect electric conductor (PEC). The designed metamaterial is anisotropic due to the polarization condition. The simulator can calculate S parameters with a high accuracy, and the retrieved electromagnetic parameters are calculated using the retrieved methods [15–17].

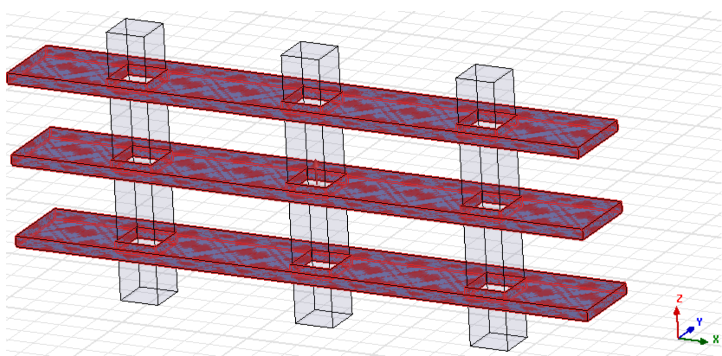


Figure 1. Anisotropic metamaterial model consists of ferrite and rods. The incident electromagnetic wave is transmitted along the Y direction. The magnetic field is in the X direction and the electric field is in the Z direction, the bias magnetic field is along Z direction. The ferrite sheets are $22.86 \times 3 \times 0.4\,\mathrm{mm}^3$ and the rods are $1.5 \times 1.5 \times 10.16\,\mathrm{mm}^3$, respectively.

The S parameters and retrieved electromagnetic parameters for individual inclusions are given in Fig. 2. As shown in Figs. 2(a)–(b), the effective permeability μ shows a resonant curve for $H = 3400$ Oe. Around 9.9 GHz, there is an S_{11} maximum corresponding to S_{21} minimum. The negative permeability appears at 9.9 GHz. As we know, if the ferrite bias magnetic field H_0 is applied along z-axis, which means transverse magnetization, by interacting with the magnetic field of an electromagnetic wave, ferromagnetic precession can arise in ferrite. The permeability of ferrite μ_1 can be described by Landau-Lifshitz-Gilbert model [18]:

$$\mu_1 = 1 - \frac{F\omega_0(\omega_0 + \omega_m)}{\omega^2 - \omega_0(\omega_0 + \omega_m) - i\Gamma(\omega)\omega} \tag{1}$$

where $\Gamma(\omega) = [\omega^2/(\omega_0 + \omega_m) + \omega_0 + \omega_m]\alpha$, α is the damping coefficient of ferromagnetic precession, $F = \omega_m/\omega_0$, $\omega_0 = \gamma H_0$ the ferromagnetic resonance frequency, γ the gyromagnetic ratio, $\omega_m = 4\pi M_s$ the characteristic frequency of ferrites, and M_s the saturated magnetization. According to Eq. (1), the permeability of the ferrite can be negative and tuned by adjusting the bias magnetic field.

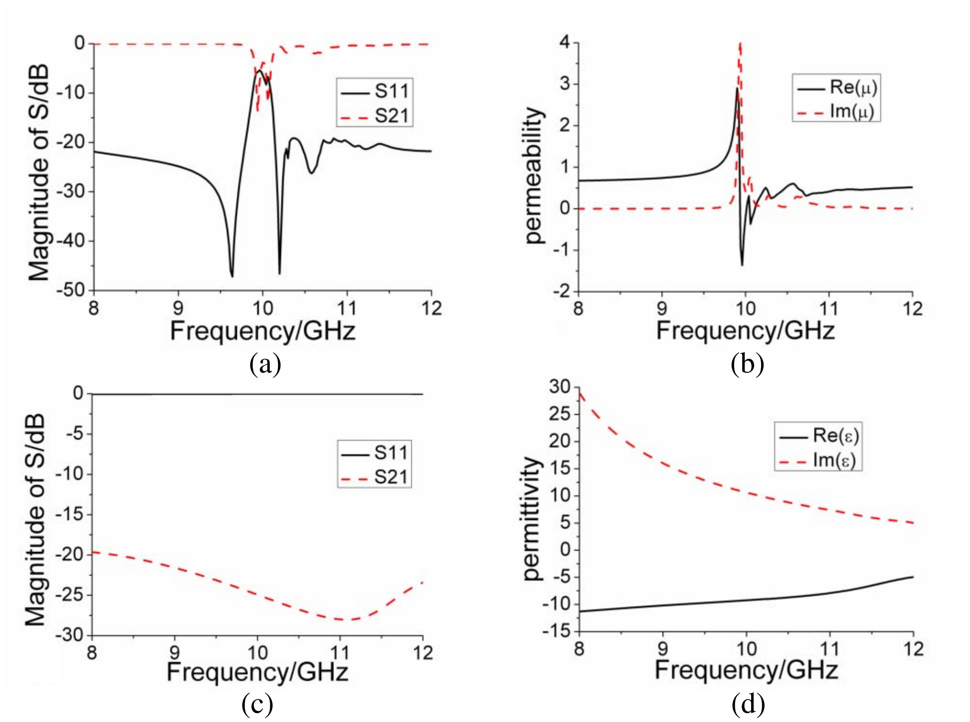


Figure 2. S parameters and the real part and imaginary part of the retrieved effective electromagnetic parameters, (a) magnitude of S for ferrite-only case, (b) effective permeability for ferrite-only case, (c) magnitude of S for rods-only case, (d) effective permittivity for rods-only case.

It should be noted that the external magnetic field H_a is not equal to the ferrite internal bias field H_0 due to the surface boundary conditions of the ferrite. When the external magnetic field is perpendicular to the ferrite sheet, based on continuity equation:

$$\mu_0 H_a = \mu_0 (M_s + H_0) \tag{2}$$

The shape of the ferrite as well as the field direction would affect the bias field between internal and external magnetic field. In this paper, the ferrite internal bias field $H_0 = H_a - M_s$.

As shown in Figs. 2(c) and (d), the effective permittivity for dielectric rods is negative in a wide range, and the electric response is similar to that of metal wires (Drude model) [19, 20]. Therefore, a combination of two inclusions with left-handed regime can be made. By adjusting parameters, the frequency range of negative permittivity can cover that of the tunable negative permeability.

As shown in Fig. 3, the effective permittivity and permeability of the composite are calculated to prove the left-handedness. The medium had a pass band near 8.8 GHz. The retrieved parameters demonstrate that the pass band was left-handed band due to simultaneous appearances of negative effective permittivity and negative permeability. Resonances both in ferrite and rods have contributions to the transmission peak.

To investigate the tunable property of the metamaterial, we vary the external magnetic field from 3000 Oe to 4000 Oe. Fig. 4 illustrates the retrieved effective electromagnetic parameters in different magnetic fields. A transmission band appears at 8.8 GHz when the applied magnetic field is 3000 Oe, which corresponds to the magnetic resonance at 8.8 GHz. When a magnetic field of H 3400 Oe is applied, the transmission band appears at 9.9 GHz. This indicates that the electromagnetic properties of the metamaterial can be affected by the applied magnetic field. The transmission band moves to higher frequencies for the increased magnetic field, which exhibits a magnetically tunable behavior. Besides, the magnetic resonance frequency of the metamaterial is essentially the same as ferrite-only case, which means that the coupling between dielectrics and ferrites can be neglected in this design.

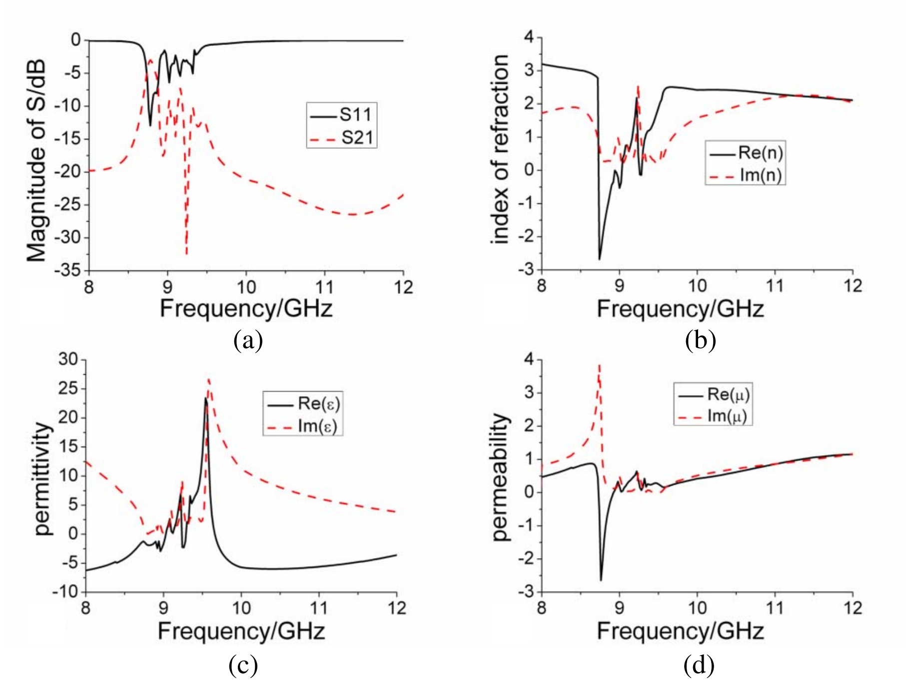


Figure 3. S parameters and the real part and imaginary part of the retrieved effective electromagnetic parameters for ferrite-dielectric metamaterial at $H = 3000$ Oe, (a) magnitude of S, (b) index of refraction, (c) effective permittivity, (d) effective permeability.

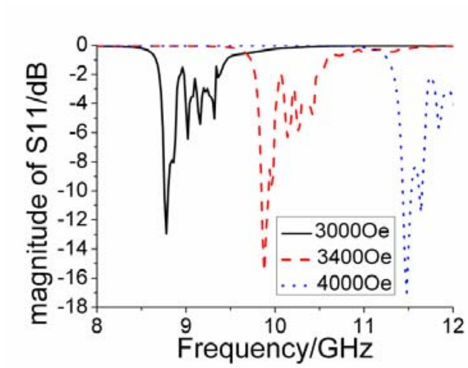


Figure 4. Transmission parameters S_{11} of the metamaterial under different bias magnetic fields.

3. EXPERIMENTS

Experimental investigations are implemented to confirm the simulation results. A photograph of the microwave measurement system is shown in Fig. 5. The measurement system is composed of X-band waveguide, vector network analyzer (HP8720ES), and electromagnet. The bias magnetic field is generated by the electromagnet and can be tuned by adjusting the input current.

The ferromagnetic material was YIG ferrite, whose saturation magnetization was 1780 Gs, and resonant bandwidth was 30 Oe. The relative permittivity is about 14.4, which is stable at microwave frequencies. The dielectric material was $Ba_{0.6}Sr_{0.4}TiO_3$ (BST), doped with $La(Mg_{0.5}Ti_{0.5})O_3$. The permittivity of BST was 100, and the loss tangent was 0.0016. The ferrite sheets were $22.86 \times 3 \times 0.4\,mm^3$, and the rods were $1.5 \times 1.5 \times 10.16\,mm^3$. Fig. 6 presents the experimental transmission spectra and effective permeability for the ferrite-only case under a 3400 Oe applied magnetic fields. A transmission dip induced by magnetic resonance occurs in the transmission spectrum. The experiment results agree

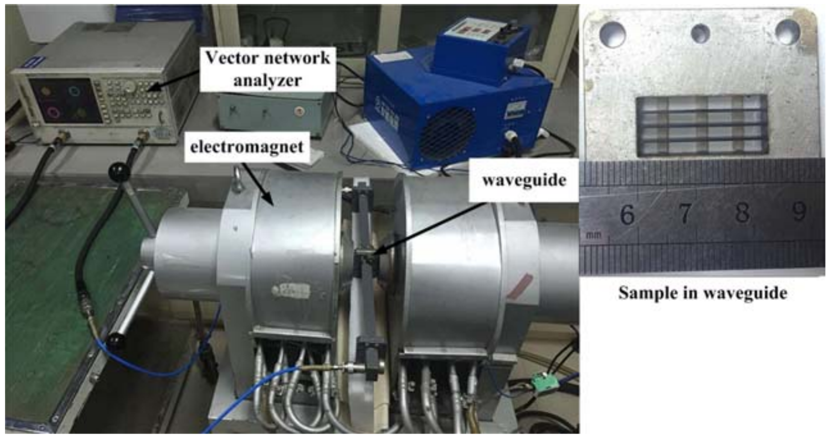
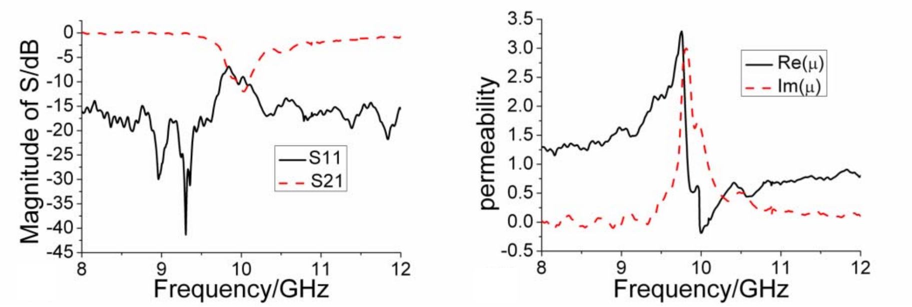
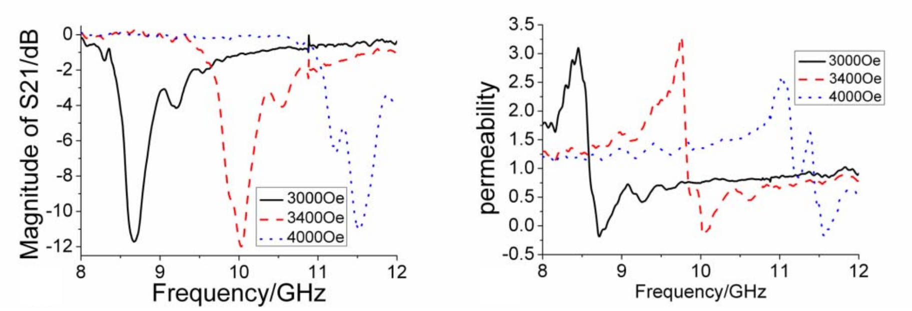


Figure 5. Experimental waveguide setup, the sample is placed between the air gap of the electromagnet. The bias magnetic field is tuned by adjusting the input current.



(a) (b)

Figure 6. (a) Experimental S parameters, (b) the real part and imaginary part of the effective permeability for ferrite-only case at $H = 3400\,\mathrm{Oe}$.



(a) (b)

Figure 7. (a) Experimental transmission parameters S_{21}, (b) the real part and imaginary part of the effective permeability for ferrite-only case under different bias magnetic fields.

well with the simulation ones, which indicate that the effective negative permeability is generated by the ferrite magnetic resonance.

When a series of magnetic field is applied, the magnetic resonance frequency changes as shown in Fig. 7.

Figure 7 shows the magnetic resonance frequency shifts to higher frequencies with increasing H.

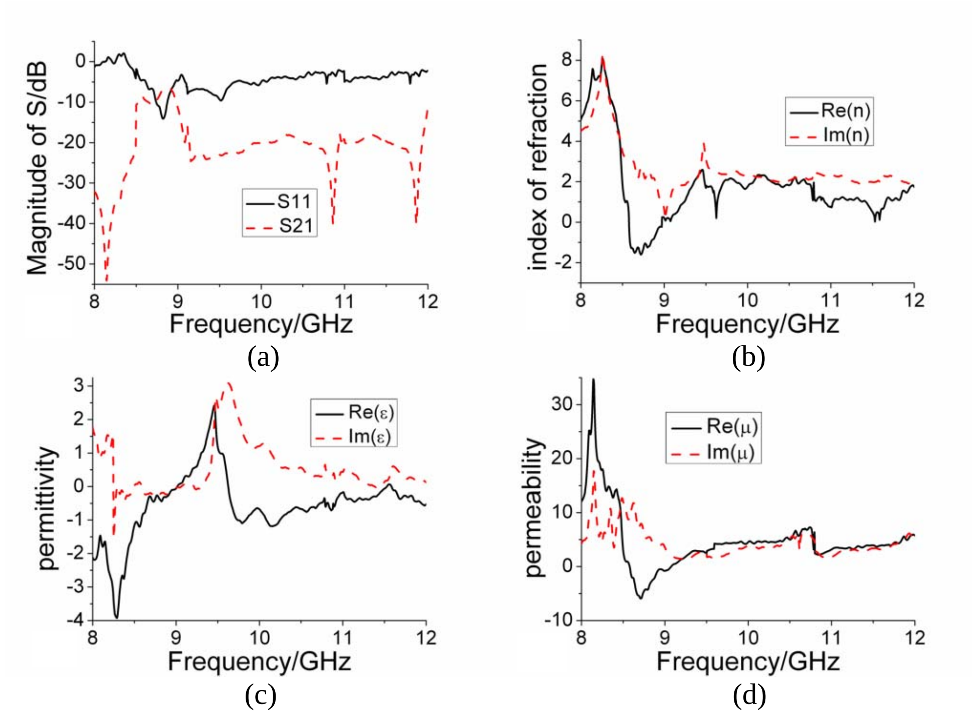


Figure 8. Experimental S parameters and the real part and imaginary part of the retrieved effective electromagnetic parameters for ferrite-dielectric metamaterial at $H = 3400$ Oe. (a) Magnitude of S, (b) index of refraction, (c) effective permittivity, and (d) effective permeability.

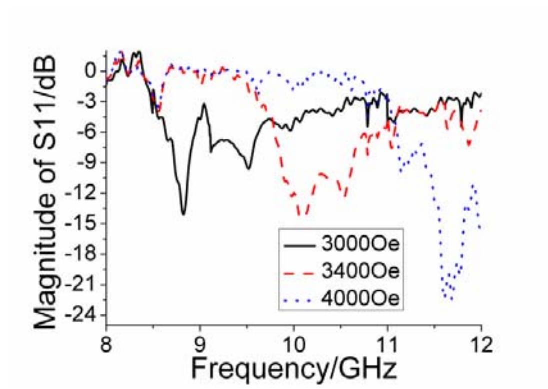


Figure 9. Experimental transmission parameters S_{11} of the metamaterial under different bias magnetic fields.

The combination of ferrite and dielectric rods were also studied in the waveguide as shown in Fig. 8. S parameters and the retrieved effective electromagnetic parameters at $H = 3000$ Oe were plotted in Fig. 8. A ferrite magnetic resonance is observed at 8.8 GHz, and the effective permeability is negative. The electric response is generated by rods, and the effective permittivity is negative in a wide range as the results of simulation. The transmission pass band at 8.8 GHz is left-handed band due to simultaneous appearance of negative refractive index, negative effective permittivity and negative permeability.

Figure 9 shows the S_{11} parameters under different magnetic bias. The transmission pass band is tunable in external magnetic fields. The magnetic resonance frequency of the metamaterial is essentially the same as ferrite-only case compared to Fig. 7. These figures clearly demonstrate that the experiment results agree well with the simulation ones.

4. CONCLUSION

We experimentally and numerically demonstrate a magnetically tunable ferrite-dielectric metamaterials. The tunable property is attributed to the ferromagnetic resonance and electric response of dielectric rods. If the ferrite bias magnetic field is applied, the permeability of ferrite has negative values in certain frequency range. The shape of the ferrite will affect the bias field between internal and external magnetic fields. The effective permittivity for dielectric rods is negative in a wide range, and the electric response is similar to that of metal wires. When the magnetic field changes from 3000 Oe to 4000 Oe, the transmission pass band appears in the range of 8.8–11.5 GHz. This demonstrates that the left-handed band of the matamaterial is tunable. Experiment and simulation results show that the coupling between dielectrics and ferrites can be neglected in this design. This characteristic brings about a simple design of tunable metamaterials.

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